IONOMR
INNOVATIONS

WHITE PAPER:

Hydrogen Production Cost by AEM Water Electrolysis

2386 East Mall - Suite 111
Vancouver, BC Canada
V6T 1Z3

BACKGROUND & INTRODUCTION

Water electrolysis was invented in the 1800s and has been used in industry for hydrogen production since the 1920s. With the increase in renewable energy's share of global electricity production, water electrolysis is a promising solution to produce low-carbon to fully green hydrogen and connect the sectors of renewable energy, heavy industry, and transportation across the entire energy system. Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Water Electrolysis (PEMWE) are the two primary methods for hydrogen production in commercial use. Alternative methods for green hydrogen production including Solid Oxide Water Electrolysis (SOWE) and Photoelectrochemical ('Artificial Leaf') systems remain in the early R&D stage.

Between the two commercial technologies, AWE is the more mature, providing durable water electrolysis systems that have been used widely for decades. AWE offers a distinct advantage of employing low-cost components including inexpensive electrode and porous transport layer materials such as nickel. However, due to the large internal resistance incurred across the thick porous diaphragm and liquid electrolyte employed, AWE normally operates at low current density (< 0.5 A/cm²) and efficiency[1]. As a result of this low areal utilization, AWE requires a bulky stack design at large (e.g. MW) scales, and stack cost and motility are major contributors to system capital costs (CAPEX). The porous separator necessitates careful pressure balancing of AWE systems. Current density must be altered slowly, and high minimum loads for operation (typically >20-50% of rated power) are required, both causing major challenges to the deployment of these systems for balancing intermittent renewable energy sources such as wind and solar power.

A number of water electrolysis manufacturers have developed commercial PEMWE systems that are now available at MW scale. PEMWE systems typically operate at higher current densities (1-3 A/cm²)[2], enabling compact designs that can be containerized even at larger scales, providing significant advantages both to manufacturing and on-site deployment. The non-porous nature of the polymeric membrane separator allows for rapid cycling in flexible operational conditions better suited to pairing with intermittent renewables, and provides a speed of response sufficient to replace grid-balancing services. Further, the membrane-type design allows for higher purity hydrogen than AWE, higher initial output pressures, and low minimum loads (typically 5% rated power). However, the use of Platinum-Group Metals (PGM) in the electrocatalyst and in particular, as the corrosion-resistant coating layers on flow components, raises the PEMWE CAPEX substantially[3,4].

The development of a low-CAPEX electrolysis system would play a vital role in reducing the production cost of green hydrogen. In their current state at the 10-100 MW-scale, the investment cost for both AWE and PEMWE systems are substantially higher than the DOE target ($300/kW). Even with the cost of intermittent renewable energy dropping below $0.02/kWh, the capital cost of these deployments is a significant impediment for green hydrogen to compete with the dominant technology of converting natural gas by Steam Methane Reforming (SMR).

An alternative electrolysis technology that has recently gained interest from industrial developers is Anion Exchange Membrane Water Electrolysis (AEMWE). The design of an AEMWE cell may be conceived either as a significant enhancement to the properties of AWE separators, both in terms of resistance and impermeability, or as a morphing of PEMWE technology that allows a similar form-factor and capabilities, with the key difference being AEM systems transport hydroxide ions (OH^-) instead of protons (H^+). This creates an alkaline electrochemical environment rather than an acidic environment, enabling significantly more cost-effective materials to be employed. As with PEMWEs, AEMWEs may use finely divided metal catalysts in close contact with a non-porous membrane and two gas transport layers to form a Membrane Electrode Assembly (MEA), or, as with AWEs, they may use strongly alkaline conditions on both electrodes to provide adequate conductivity to mesh electrodes.

THE NEED FOR A DISRUPTIVE TECHNOLOGY

AEMWEs can combine and improve upon advantages of both AWE and PEMWE systems. Compared to PEMWE systems, they operate in dilute liquid alkaline electrolyte instead of pure deionized water, providing tolerance to impurities, flexible electrode design, and an advantage in large systems. AEMWEs can operate at high current densities with differential pressures while using low to zero PGM loadings for the catalyst layers or electrodes. The plenitude of materials choices for corrosion resistance in alkaline media eliminate the need for PGM-coated titanium as the porous transport media and other flow components. In addition, with dilute KOH concentrations (e.g. 1-2 M), shunt currents are substantially reduced for added efficiency and the Balance of Plant (BOP) can be simplified over existing AWE technology with fewer safety concerns and improved material compatibility for supporting equipment.

AEMWE is an extremely promising technology to reduce the capital cost of electrolysis systems. However, this technology is currently only available at small scale and in the early stages of development for exploitation at large scales. Instability of key components, in particular membranes, as well as catalysts and electrodes, with additional difficulties of sealing small systems to CO_2 from ambient air, have caused significant obstacles to the commercialization and scaling of AEMWEs to date[2]. The advantages and disadvantages of the three water electrolysis technologies mentioned above are summarized in **Table 1.**

The advanced alkaline stability recently demonstrated by Ionomr Innovations' Aemion+™ polymers shows the most promise out of any commercially available AEMs to enhance the stability of AEMWE, and subsequently a platform for optimization of performance of catalysts and electrodes[5]. Aemion+™ is the first available commercial material with chemical stability in conditions in excess of the harshest alkaline electrolysis systems (2-3M KOH, 80-100 C), combined with the mechanical strength and consistency to produce large areas. As a result, Aemion+™ is the enabling, platform material for the scale-up of AEMWE technology to a commercial size.

Description	AWE	PEMWE	AEMWE
Technology readiness	+	+	-
Non-PGM loading	+	-	+
Long term stability	+	0	-
MW scale	+	+	-
Compact design	-	+	+
Current density	-	+	+
Cost effective	0	-	+
Operating pressure	-	+	+
Non-corrosive environment	-	-	+

Table 1. Advantages & disadvantages of the three water electrolysis technologies

As a nascent commercial technology, performance and economic comparisons of AEMWE systems in relation to both benchmark AWE and PEMWE systems at large scales is not available. In order to raise the profile of the step-change in economic potential of AEMWE for the production of green hydrogen and the enabling role the newly developed Aemion+™ membranes play in this revolutionary technology, Ionomr has invested efforts together with pioneering industrial partners in PEMWE and AWE technologies, and leaders in the development and implementation of AEM systems, to evaluate the economic potential of this technology. The focus of this study is to determine the investment cost of AEMWE systems when the technology is available at commercial scales comparable to the latest large-scale deployments of AWE and PEMWE systems. This investment cost is applied to determine the production cost of hydrogen by water electrolysis under different electricity supply scenarios, considering the differences in technical requirements and efficiency among the three water electrolysis technologies.

COMPARISON OF WATER ELECTROLYSIS STACK DESIGN

The techno-economic analysis was started by defining system diagrams and primary specifications for each type of water electrolysis systems. The list of the major components and materials in the cell stack for three types of water electrolysis systems is given in **Table 2**, using typical design choices among existing and developmental electrolysis systems[6,7]. Among the three electrolysis technologies, the commercial AWE cell has the simplest design which includes electrodes, diaphragms, bipolar plates, gaskets and frames.

In the AWE cell, a Ni-based coating applied directly to expanded metal mesh provides the electrocatalyst, which is the most cost-effective design among the three types of water electrolysis. Based on the reported values for catalyst loadings, the cost of the AWE catalyst per unit area is estimated to be 5x and 60x less than AEMWE and PEMWE, respectively. Recently, advanced, pressurized alkaline systems capable of producing hydrogen at 30 bar, have been developed to increase current density by employing a similar electrode style with low loadings of precious metals, a similar design tradeoff found in the membrane chlor-alkali industry.

Anode	**AWE**	**PEM**	**AEM**
OER catalyst Material	Ni-based	75% IrO_2 (typical)	NiMo (e.g.)
Catalyst Loading (g/m^2)	50	20	20
Catalyst price ($\$/m^2$)	21	1238	100
Membrane	Diaphragm	PFSA (Nafion^{TM})	Aemion+^{TM}
Ionomer loading (g/m^2)	-	2.73	2.73
PTL material	-	Ti 30% porosity/Pt	Ni foam
Cathode	**AWE**	**PEM**	**AEM**
HER catalyst material	Ni-based	50% Pt/C (typical)	NiCrMo (e.g.)
Catalyst loading (g/m^2)	50	5	20
Catalyst price ($\$/m^2$)	21	195	100
Ionomr loading (g/m^2)	-	10	10
GDL material	-	Carbon cloth	Carbon cloth
Sealant/Frame	PPS-40GF	PPS-40GF	PPS-40GF
Bipolar plate material	Stainless steel	Stainless steel	Stainless steel
Bipolar coating	Ni	Pt	Ni

Table 2. High-level main components and material of different water electrolysis cell stacks

The PEMWE and AEMWE design used in this study employ the same cell architecture and similar designs based around non-porous ion-exchange membranes. The central part of the electrolysis cell is the Membrane Electrode Assembly (MEA), which is comprised of a membrane at the center, porous electrodes comprised of a electrocatalyst & ionomer mixture on either side of the membrane, and porous transport layers are applied on top of the electrodes. The catalyst and ionomers can be coated on the Porous Transport Layers (PTLs) or on both sides of the membrane to form what are commonly called Gas Diffusion Electrodes (GDEs) or Catalyst-Coated Membranes (CCMs), respectively. The PTL is typically comprised of a carbon Gas Diffusion Layer (GDL) at the cathode and metal foam or sintered porous metal at the anode. The PTL provides an electrical connection from the bipolar plate to the catalyst layer in addition to allowing the diffusion of the electrolyte or water to the surface of the membrane and enhancing the escape of produced gas bubbles.

While PEMWE and AEMWE share a similar cell design, significant differences exist in terms of material and operating conditions. The catalysts in PEMWE need to be made of platinum-group metals (PGM) such as platinum and iridium as highly active electrocatalysts with the necessary longevity withstand the acidic electrochemical environment. By contrast, the catalyst in AEMWE can be free of PGM or reduce the amount of PGM by replacing at least one of the catalysts with base metal or metal alloy electrocatalysts, with necessarily high activities and longevities enabled by the alkaline operating environment. Even when using PGM catalysts, the expensive Ir anode catalyst can be replaced with lower cost options, while in PEMWE the Ir catalyst is a necessity. The Pt-based and Ir-based catalysts are significantly more expensive than Ni-based catalysts, and as seen in **Table 2**, can be 35x more expensive than the Ni-based coatings of AWE.

However, even when using equivalent PGM catalysts in the near term, e.g. due to their commercial availability, consistency, and existing knowledge related to PEM electrode design, AEMWEs offer significant cost reduction opportunities, particularly through eliminating PGM coated titanium flow components required in PEMWE systems. Leveraging knowledge around PEM electrode design, efficiency improvement opportunities exist from a combination of the lower crossover of the membranes vs. fluorinated PEMs, the altered electrocatalytic environment in alkaline, and the benefits of ionically and electronically conducting feed liquids for the development of catalyst layers. For a given target of hydrogen output, this results in more efficient systems, or for an output/efficiency target, this results in higher volumetric and gravimetric density.

COMPARISON OF WATER ELECTROLYSIS BALANCE OF PLANT

To determine the cost of the BOP for a water electrolysis system, we collected data from literature and received inputs from our industry partners. When gathering information from different manufacturers, the BOP cost was available at different system sizes, and a cost-to-capacity approach[12] was used to normalize the BOP cost for 1 MW and 5 MW systems based on stack sizes of 200 kW and 1 MW. Since AEMWE systems are under development, there are no presently available reported values for the component cost breakdown of the BOP to the best of our knowledge. To determine the cost of BOP for AEMWE systems, we consulted technical experts about the differences in BOP of AEMWE, PEMWE, and AWE systems. The BOP cost was estimated by evaluating the technical requirement of each component in AEMWE systems and benchmarking versus AWE and PEMWE systems. The main components of the BOP include power supplies, process components and control systems, hydrogen processing, hydrogen compressors, cooling and water treatment system.

Power supplies of a given rated power, are expected to be the same specification among all systems. The power supplies include a low voltage transformer, an AC/DC rectifier, and a control system designed to supply current to the cells in the stack. The cost of power supplies is $220/kW and $165/kW for a 1 MW and 5 MW system, respectively. This has been identified as a probable area for improvement; however, at the time of writing this report, there is no published data to support a larger reduction in the power supply cost.

Hydrogen processing in AEMWE BOP systems is less complex compared to AWE. For comparison, the electrolyte in AEMWE is typically a considerably lower concentration than in AWE, which is typically reported as 1 M KOH, compared to 6-7 M KOH concentration in an AWE system[1]. With less corrosive electrolyte, the balance of the plant can be simplified by eliminating the corrosion-resistant coating requirements in the separators, piping, and pumps, by reduced requirements for electrolyte concentration monitoring[13], and through the inherently higher purity hydrogen produced from a membrane-based system. Because of that, the hydrogen processing cost in the AEMWE is approximately 20% lower cost than AWE.

	AWE		Pressurized AWE		PEMWE		AEMWE	
System capacity	1 MW	5 MW	1 MW	5 MW	1 MW	5 MW	1 MW	5 MW
Power supply & control ($/kW)	$220	$165	$220	$165	$220	$165	$220	$165
Process components ($/kW)	$158	$47	280	$83	$187	$55	$190	$56
Water treatment system ($/kW)	$19	$10	$19	$10	$23	$12	$19	$10
Hydrogen processing ($/kW)	$76	$49	$76	$49	$69	$37	$69	$37
Cooling ($/kW)	$44	$23	$44	$23	$88	$29	$44	$23
Intermediate compressor 30b ($/kW)	$279	$147						
Total BOP	**$796**	**$441**	**$640**	**$336**	**$587**	**$298**	**$542**	**$291**

Table 3. List of the main components in the balance of plant and cost estimation.

Another major difference between AEMWE and AWE is the operating pressure. AEMWE can operate up to 30 bar differential pressure while a typical AWE system operates between atmospheric and 15 bar balanced pressure. Operating at higher pressures reduces the cost of the BOP by reducing downstream compression requirements[14]. The reduced crossover increases the potential operating range of AEMWE to a similar window as PEMWE (~5% minimum load) making it particularly suitable for pairing with renewable energy in comparison with AWE technology (>20% minimum load). Due to balanced pressure requirements, AWE BOP requires pressure piping on the on the oxygen side while AEMWE BOP can utilize an atmospheric design similar to PEMWE. Based on input from water electrolysis manufacturers, when operating at a pressure of 30 bar, the process components are roughly 30% more expensive than a system operating at 10 bar.

For other utilities, the cost of water purification for AEMWE is similar to AWE and about 10-20% lower than PEMWE. This is due to strict requirements for deionized water purity in PEMWE system, while the supporting alkaline electrolyte can tolerate higher impurity levels. Since the AEMWE and AWE systems operate with liquid electrolytes and do not have high rejected heat, it has been suggested by a manufacturer that the cost of cooling systems in AEMWE and AWE can be 50% of PEMWE.

Based on these comparisons, we estimate the BOP cost for AEMWE and pressurized AWE using recent literature [4,15]. We acknowledge that these comparisons do not realize differences between the two systems in detail but provide a certain estimation on the investment cost of pressurized AWE systems and AEM systems that is not available in the public domain. The estimation of BOP for each water electrolysis type is given in **Table 3**.

THE PERFORMANCE OF WATER ELECTROLYSIS SYSTEMS

Cell stack design and performance of the three types of water electrolysis systems are summarized in **Table 4**. AWE and PEMWE specifications are reported based on existing systems obtained from literature and commercial datasheets. While the working current density in normal AWE systems is less than 0.5 A/cm^2, advanced Ru-based catalysts in pressurized AWE systems can increase the current density to 0.8 A/cm^2. Note that the advanced Ru-based catalyst coating is reported as at least 8 times more expensive than common Ni-based coatings in AWE systems. Different types of catalyst material were also considered for AEMWE systems. In the first scenario, we considered an AEMWE system without using PGM catalysts. In this scenario, the current density of the cell was considered to be 0.8 A/cm^2 at 1.8 V to be consistent with advanced AWE conditions. While in the second scenario, the PGM catalyst loading was the same as PEMWE. Based on test results at partner facilities, PGM catalysts increased the performance of the AEMWE system to greater than 1.5 A/cm^2 at 1.8 V. This was achieved using an Ir-based anode and Pt-based cathode. However, unlike PEMWE, the Ir-based catalyst can be replaced with less expensive PGM catalysts, while PEMWE must use high-cost Ir-based catalysts to function.

Similar performance has been demonstrated using non-precious anode catalysts[9–11]. Validation of catalyst stability and commercialization of these non-PGM anode catalysts[9–11] while minimizing PGM loading on the cathode (i.e. 0.5 mg/cm^2 or less) remains a focus of development. This will provide a further reduction in cell cost as well an improvement to supply chain security through elimination of iridium, however has not yet been considered in this analysis. To enable direct comparison with the results of the NREL cost analysis, two systems sizes were considered: a 1 MW system comprised of 200 kW stacks and 5 MW system co mprised of 1 MW stacks.

Parameters	AWE	Pressurized AWE	PEMWE	AEMWE with non PGM loading	AEMWE with PGM loading
Current density (A/cm^2)	0.4	0.8	1.8 - 3	0.8	1.5
Cell voltage (V)	1.8	1.8	1.9	1.8	1.8
Operating pressure (bar$_g$)	0-10	0-30	0-30	0-30	0-30

Table 4. Main Characteristics of water electrolysis systems

←

COSTING APPROACH AND CONSIDERATIONS

A techno-economic analysis was prepared to evaluate the economic performance of the five different water electrolysis systems. The assessment was carried out under two deployment scenarios – small-scale production of 1 MW systems and large-scale production of 5 MW systems. The first scenario reflects the early state of deployment of water electrolysis technology and a production volume of 100 systems per year. As this technology proves its efficiency and economic viability, the expected production volume of 5 MW system scale is projected to become 1000 systems/year. This deployment of 5 GW systems tracks well within the International Renewable Energy Agency (IRENA)[16] projected need for 1700 GW of electrolyzer capacity to be deployed in order to meet the 'Transforming Energy Scenario' for decarbonization that meets the Paris Agreement targets to ensure global warming below 1.5 °C. **Table 5**. Deployment scenarios of water electrolysis systems at small- and large-scale production volume. summarizes the assessment scenarios for two production volumes.

Scenarios	Water electrolysis technologies	Stack capacity	System capacity	Production scale
Small scale production	- AWE - Pressurized AWE - PEMWE - AEMWE with non-PGM catalysts - AEMWE with PGM catalysts	200 kW	1 MW	100 systems/year
Large scale production	- AWE - Pressurized AWE - PEMWE - AEMWE with non-PGM catalysts - AEMWE with PGM catalysts	1 MW	5 MW	1000 systems/year

Table 5. Deployment scenarios of water electrolysis systems at small- and large-scale production volume.

RESULTS & DISCUSSIONS

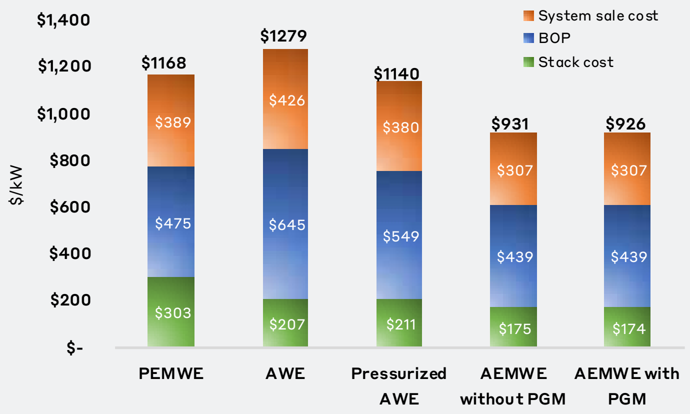
INVESTMENT COST OF WATER ELECTROLYSIS SYSTEMS

The investment cost of the five water electrolysis systems is presented below. At 1 MW scale, the investment costs of AWE and PEMWE systems are similar and equal to $1279/kW and $1168/kW, respectively. The pressurized AWE system cost is at least 10% lower than the normal AWE systems with peripheral compressors. At low current density, the investment cost of 1 MW AEMWE systems is $922/kW, which is lower than either AWE or PEMWE systems of the same size. As current density increases with loading of PGM catalyst in AEMWE systems, the AEMWE system cost is $921/kW which is the lowest value among the five assessed technologies at the 1 MW scale and limited production quantity.

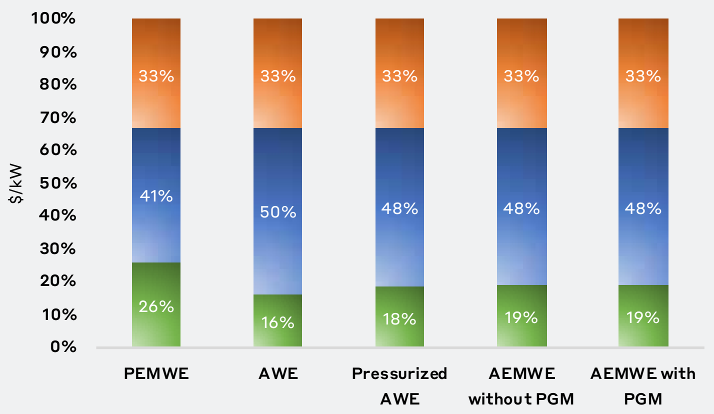
When scaling up the system size from 1 MW to 5 MW, and production volume from 100 systems/year to 1000 systems/year, the investment cost is greatly reduced across three technologies. In particular, the specific capital cost of large water electrolysis systems in mass production decreases between 45%-50% compared to small systems. Mainly, scale-up of the electrolyzer size allows peripheral components to be designed at optimal scales and increase material utilization. Increasing the production volume also decreases the investment cost through improvements in manufacturing processes, inventory management, as developing a robust supply chain. The estimated costs of 5 MW PEMWE and AWE systems are $587/kW and $596/kW, respectively. Meanwhile, pressurized AWE system costs are approximately $554/kW. At low current density and high current density with PGM loading, AEMWE system costs are below other commercial water electrolysis systems at approximately $444/kW and $459/kW, respectively.

The investment cost of the five water electrolysis systems is presented below. At 1 MW scale, the investment costs of AWE and PEMWE systems are similar and equal to $1279/kW and $1168/kW, respectively. The pressurized AWE system cost is at least 10% lower than the normal AWE systems with peripheral compressors. At low current density, the investment cost of 1 MW AEMWE systems is $922/kW, which is lower than either AWE or PEMWE systems of the same size. As current density increases with loading of PGM catalyst in AEMWE systems, the AEMWE system cost is $921/kW which is the lowest value among the five assessed technologies at the 1 MW scale and limited production quantity.

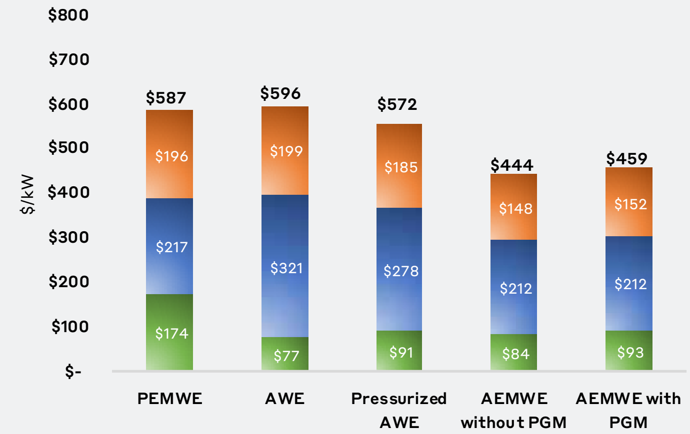
(a) Investment cost of 1 MW electrolysis systems



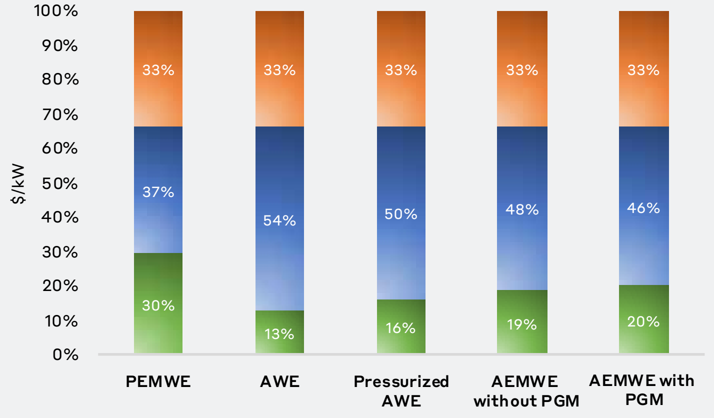
(b) Cost breakdown of 1 MW electrolysis systems investment cost



(c) Investment cost of 5 MW electrolysis system



(d) Cost breakdown of 5 MW electrolysis systems investment cost

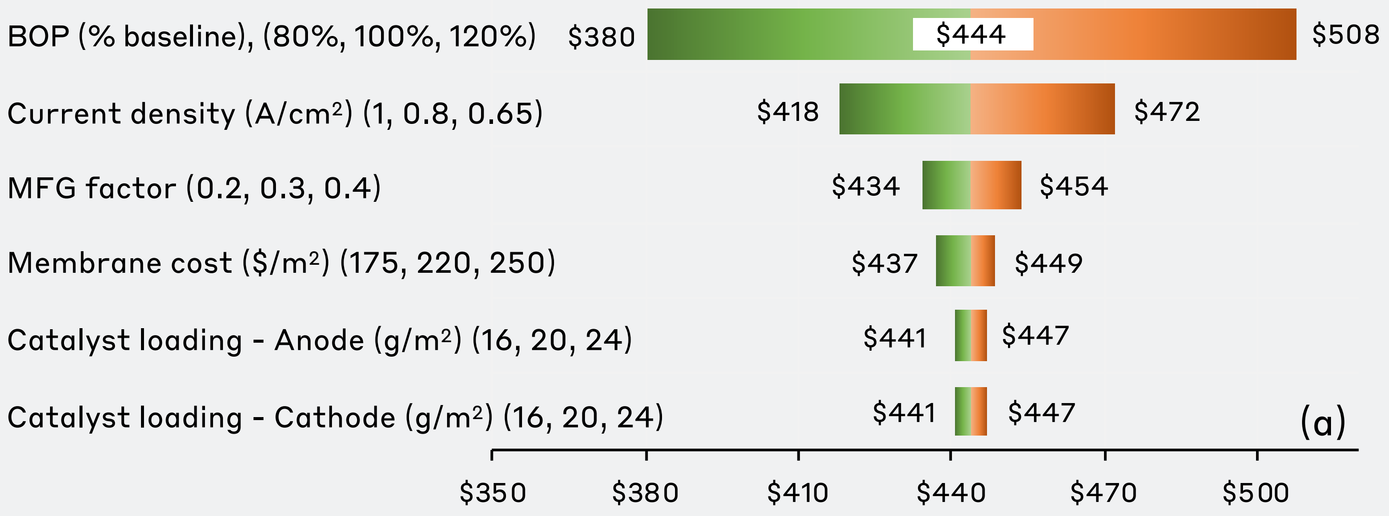


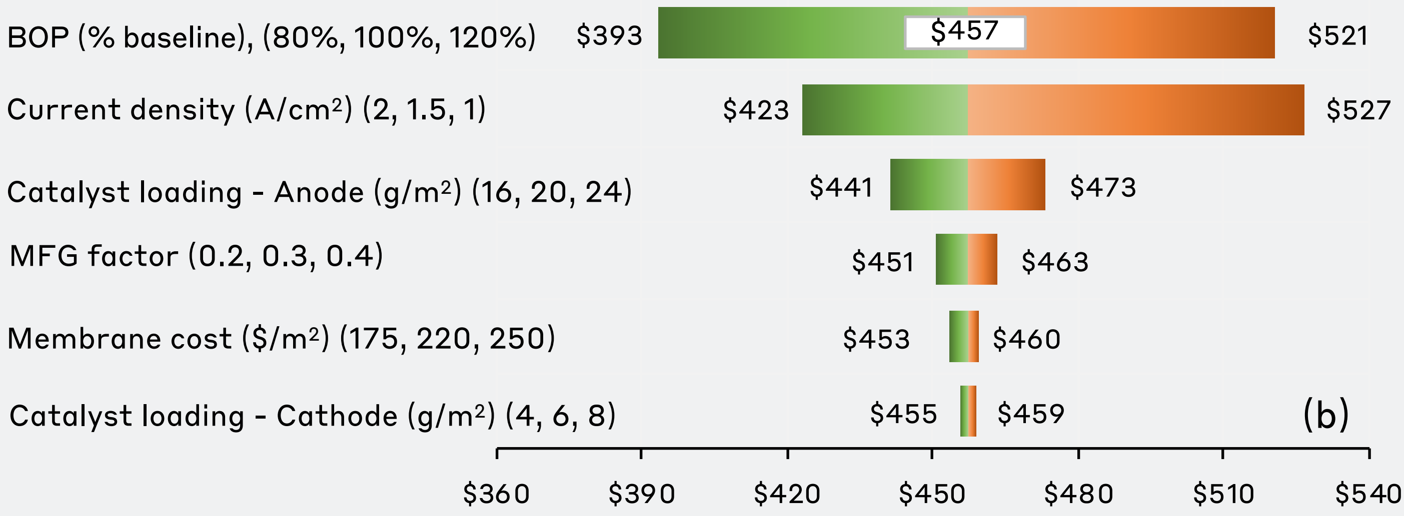
RESULTS & DISCUSSIONS

INVESTMENT COST OF WATER ELECTROLYSIS SYSTEMS

When scaling up the system size from 1 MW to 5 MW, and production volume from 100 systems/year to 1000 systems/year, the investment cost is greatly reduced across three technologies. In particular, the specific capital cost of large water electrolysis systems in mass production decreases between 45%-50% compared to small systems. Mainly, scale-up of the electrolyzer size allows peripheral components to be designed at optimal scales and increase material utilization. Increasing the production volume also decreases the investment cost through improvements in manufacturing processes, inventory management, as developing a robust supply chain. The estimated costs of 5 MW PEMWE and AWE systems are $587/kW and $596/kW, respectively. Meanwhile, pressurized AWE system costs are approximately $554/kW. At low current density and high current density with PGM loading, AEMWE system costs are below other commercial water electrolysis systems at approximately $444/kW and $459/kW, respectively.

To validate our assumptions, a sensitivity analysis was performed on the total investment cost. The sensitivities of key parameters on the investment cost of 5 MW AEMWE systems are shown in the figure bleow. The current density and the BOP cost have the largest impact on the investment cost among the assessed parameters. We have invested our efforts to validate and improve the accuracy of these parameters in the model. Particularly, reported values of the current density were taken from internal and partner test results that are stable, reliable and conservative in comparison with highest performance achieved. The estimation of the BOP reflects our best estimation with available data sources, cross-validated with reported values and internal feedback from electrolyzer manufacturers. The BOP cost is particularly difficult to quantify, as this remains confidential information of individual manufacturers. There is particular room for improvement in the BOP costs and a bottom up sizing and costing of individual BOP systems remains a target for further study.



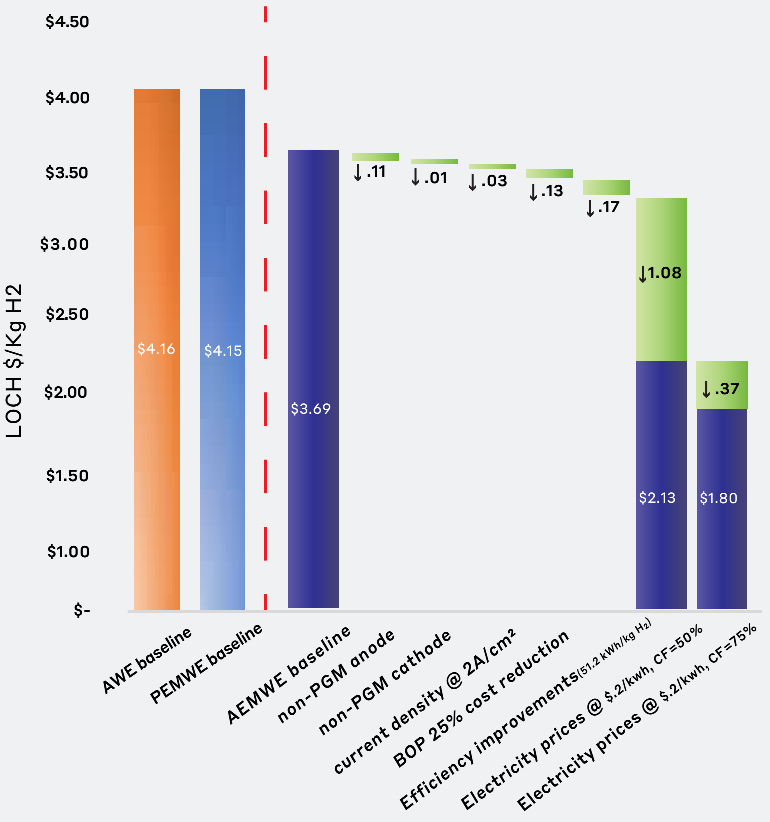


HYDROGEN PRODUCTION COST BY AEMWE

AEMION+™ IS ENABLING LARGE SCALE COMMERCIAL DEVELOPMENT

AEMWE investment cost can be further reduced by leveraging advanced non-PGM catalysts, particularly on the anode side to replace expensive Ir-based OER catalysts. Partner test results have shown promising performance indicating that the current density of AEMWE with advanced non-PGM catalysts can approach current PEMWE performance and there is a current focus on validating and maintaining the stability of these catalysts at a commercial production scale. The estimated cost, which is based on catalyst loading conditions in a lab-scale electrolysis cell design, shows a possible 30% to 40% further cost reduction in the AEMWE stack BOM. This is a promising projection of future cost reductions in AEMWE technology. Combined with the optimization of the BOP in large scale electrolysis plants, there are many opportunities to bring down the AEMWE system investment cost below $400/kW in short term developments, and to meet the DOE targets of $300/kW over longer-term developments. Aemion+™ is a non-porous ion exchange membrane which demonstrates stability in the harsh operating conditions of AWE[20], and provides a highly interesting possibility for direct replacement of porous diaphragms with impermeable Aemion+TM membranes. This provides the opportunity to create a hybrid pressurized AWE system with a simplified control system and improved turndown ratio to match that of PEMWE, enabled by the order of magnitude reduction in hydrogen crossover, without substantial investment in redesign of the cell stack. The cost impact has not been quantified in this report due to substantial uncertainty around the existing and modified BOP design, however remains an interest for further study or collaboration.

These results indicate the capital cost effectiveness of AEMWE systems, which are >25% less than AWE and PEMWE, and still >20% less than the most competitive pressurized alkaline systems. With the enabling use of Aemion+TM as the first commercial strong alkaline stable anion-exchange membranes, AEMWE technology has reached the point where these systems can be confidently scaled up. Performance of AEMWE can approach PEMWE performance in the near term employing a comparatively low loading of PGM catalysts, and costs further improved by commercialization of stable, high performance, non-PGM anode catalysts. Currently, scale up of water electrolysis is gaining attention to meet the growing demand for energy storage and sector coupling via power-to-gas and hydrogen-to-power systems. Our analysis represents a positive indicator that the investment cost of AEMWE systems in large-scale deployment scenarios will be the first and only electrolysis technology to meet and exceed DOE targets for capital cost. With further improvements and better insight into the BOP costs, as well as the production of stable, Non-PGM anode catalysts, this target is readily achievable using AEMWE while no clear path can be seen for either PEMWE or AWE.

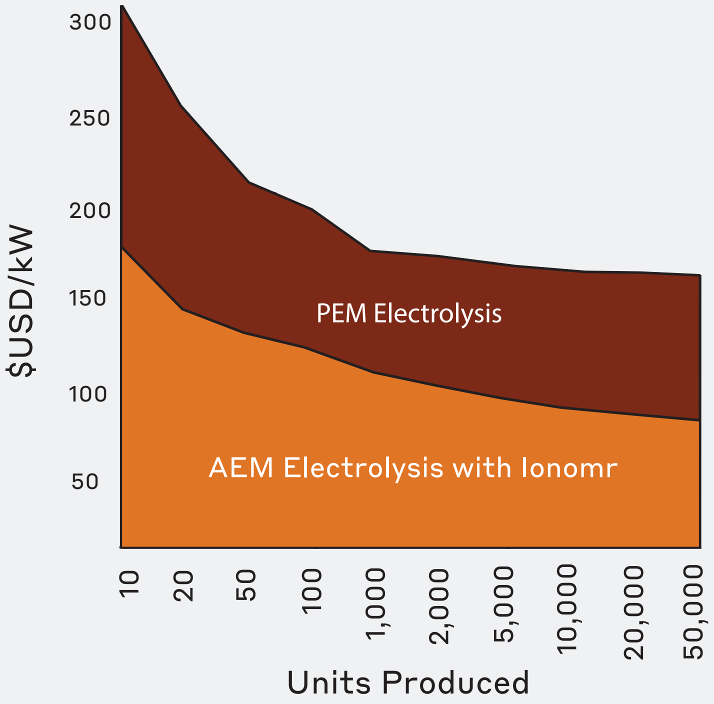


The H2A model[19] was used to study the effect of the capital cost of AEMWE systems on the hydrogen production cost. This H2A model includes direct capital cost, feedstock cost, and fixed operation cost related to capital investments such as taxes, insurance, scheduled maintenance cost, etc. The lifetime of the plant is considered to be 20 years. Land rental, administration, and development costs vary across regions and are not included in this study. Stack replacement cycle for the AEMWE is considered similar to PEMWE, which is double of AWE. This reflects the shorter lifespan of the membrane in PEMWE and AEMWE. To date, the lifetime of AEM materials has limited the commercial viability of AEMWE system. In-situ lifetime tests are ongoing using Aemion+, with ex-situ stability indicators of indefinite polymer stability, including a study of 0% chemical degradation in 10 M KOH at 100 oC[20] and a small molecule study indicating half-lives >10,000 h[5].

For the baseline, the Levelized Cost of Hydrogen (LCOH) was investigated using 5 MW AEMWE plants at $460/kW. However, in order to consider the effect of future investment cost, we leveraged our capital improvement roadmap for AEMWE technology in the LCOH assessment. This improvement roadmap is based on current focus areas, which are in line with partners across the value chain to further drive the electrolyzer system cost toward DOE targets.

CONCLUSION

AEMION+™ IS ENABLING LARGE SCALE COMMERCIAL DEVELOPMENT



The pathway to lower the cost of electrolytic hydrogen is possible with the advance of AEMWE technology. Using Aemion+™ membrane by Ionomr Innovations, AEM stability has improved to a point enabling large scale commercial development, and performance can be improved based on a stable platform to approach PEMWE. Ionomr is collaborating with industrial partners and research institutes globally to scale up this technology and fully validate its durability and performance to prove out the value proposition of AEMWE for the provision of energy efficient and low-cost green hydrogen.

When scaling up capacity and production volume, the investment cost of AEMWE electrolysis systems is the most feasible candidate to meet and exceed DOE targets of $300/kW through further advances to system BOP costs, and stable high-performance non-PGM catalysts. Near-term cost improvements are also possible in pressurized AWE by increasing operating range using Aemion+™ membranes. Combined with low-cost electricity available from the mass deployment of intermittent renewable energy, low carbon hydrogen production by water electrolysis is readily achievable at ≤ $2/kg with AEM Water Electrolysis technology.

ABOUT IONOMR

Ionomr is a clean technology company that develops and markets ion-exchange membrane and polymer solutions for fuel cell systems, hydrogen production, and a range of energy storage applications. Our products enable product developers and integrators to optimize their product performance, improve durability, eliminate toxic components, increase recyclability, and accelerate down the cost curve earlier than anticipated. Our R&D and manufacturing facilities are based in Vancouver, Canada, a key worldwide hub for fuel cell and electrochemical systems research and development.

Electrochemical fuel cell and energy storage systems have historically used membrane materials and polymers containing perfluorinated compounds, or PFCs/PFAS. These compounds break down very slowly in our environment, leak into water sources, and accumulate biologically in people and other living organisms. The adverse effects of PFC-related pollution provided the impetus for Ionomr to pioneer the development of ion-exchange membranes using modern green chemistry techniques that are non-toxic to our environment. As Ionomr produces its membranes and polymers from a hydrocarbon base, they are fully recyclable and recoverable, non-bio-accumulative, and are ideal replacements for current membrane and polymer products containing PFCs/PFAS.

Aemion™ and Aemion+™ are an ultra-stable class of anion exchange membranes (AEMs) that operate in strong alkaline media and enable electrochemical systems without the need for precious metals (commonly platinum and iridium) required by systems with acidic electrochemical environments based on proton-exchange membranes. Ionomr employs advanced molecular design and green hydrocarbon/fluorine-free chemistry, pioneering new production methodologies to offer a step-change in membrane durability, to offer the very minimal environmental impact as a critical component of the electrochemical systems underlying the hydrogen economy and efficient carbon capture/utilization.

REFERENCES

(1) Ursúa, A.; Gandía, L. M.; Sanchis, P. Hydrogen Production from Water Electrolysis: Current Status and Future Trends. In Proceedings of the IEEE; Institute of Electrical and Electronics Engineers Inc., 2012; Vol. 100, pp 410–426. https://doi.org/10.1109/JPROC.2011.2156750.

(2) Vincent, I.; Kruger, A.; Bessarabov, D. Hydrogen Production by Water Electrolysis with an Ultrathin Anion-Exchange Membrane (AEM). Int. J. Electrochem. Sci. 2018, 13 (12), 11347–11358. https://doi.org/10.20964/2018.12.84.

(3) Shiva Kumar, S.; Himabindu, V. Hydrogen Production by PEM Water Electrolysis – A Review. Mater. Sci. Energy Technol. 2019, 2 (3), 442–454. https://doi.org/10.1016/j.mset.2019.03.002.

(4) Mayyas, A.; Ruth, M.; Pivovar, B.; Bender, G.; Wipke, K.; Mayyas, A.; Ruth, M.; Pivovar, B.; Bender, G.; Wipke, K. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. 2019, No. August.

(5) Fan, J.; Willdorf-Cohen, S.; Schibli, E. M.; Paula, Z.; Li, W.; Skalski, T. J. G.; Sergeenko, A. T.; Hohenadel, A.; Frisken, B. J.; Magliocca, E.; Mustain, W. E.; Diesendruck, C. E.; Dekel, D. R.; Holdcroft, S. Poly(Bis-Arylimidazoliums) Possessing High Hydroxide Ion Exchange Capacity and High Alkaline Stability. Nat. Commun. 2019, 10 (1), 1–10. https://doi.org/10.1038/s41467-019-10292-z.

(6) Ayers, K.; Danilovic, N.; Ouimet, R.; Carmo, M.; Pivovar, B.; Bornstein, M. Perspectives on Low-Temperature Electrolysis and Potential for Renewable Hydrogen at Scale. 2019. https://doi.org/10.1146/annurev-chembioeng.

(7) Belletti, A.; Britton, B. Ionomr Innovations Inc . Anion Exchange Membranes : The Most. 2019, No. July, 1–14.

(8) Fortin, P.; Khoza, T.; Cao, X.; Martinsen, S. Y.; Oyarce Barnett, A.; Holdcroft, S. High-Performance Alkaline Water Electrolysis Using AemionTM Anion Exchange Membranes. J. Power Sources 2020, 451 (November 2019). https://doi.org/10.1016/j.jpowsour.2020.227814.

(9) Wang, L.; Weissbach, T.; Reissner, R.; Ansar, A.; Gago, A. S.; Holdcroft, S.; Friedrich, K. A. High Performance Anion Exchange Membrane Electrolysis Using Plasma-Sprayed, Non-Precious-Metal Electrodes. ACS Appl. Energy Mater. 2019, 2 (11), 7903–7912. https://doi.org/10.1021/acsaem.9b01392.

(10) Sheng, W.; Bivens, A. P.; Myint, M.; Zhuang, Z.; Forest, R. V.; Fang, Q.; Chen, J. G.; Yan, Y. Non-Precious Metal Electrocatalysts with High Activity for Hydrogen Oxidation Reaction in Alkaline Electrolytes. Energy Environ. Sci. 2014, 7 (5), 1719–1724. https://doi.org/10.1039/c3ee43899f.

(11) Li, X.; Liu, G.; Popov, B. N. Activity and Stability of Non-Precious Metal Catalysts for Oxygen Reduction in Acid and Alkaline Electrolytes. J. Power Sources 2010, 195 (19), 6373–6378. https://doi.org/10.1016/j.jpowsour.2010.04.019.

(12) Desai, A.; Mital, A. Production Economics : Evaluating Costs of Operations in Manufacturing and Service Industries.

(13) Ayers, K. E.; Anderson, E. B.; Capuano, C. B.; Niedzweicki, M.; Hickner, M.; Wang, C.-Y.; Len, Y.; Zhou, W. Characterization of Anion Exchange Membrane Technology for Low Cost Electrolysis. https://doi.org/10.1149/04523.0121ecst.

(14) Emile, M. S.; Ojong, T.; Georg, I.; Gutachter, M.; Hans, I.; Krautz, J.; Heinz, I.; Berg, P. Characterization of the Performance of PEM Water Electrolysis Cells Operating with and without Flow Channels, Based on Experimentally Validated Semi-Empirical Coupled-Physics Models1976 in Kumba-Kamerun. 2018.

(15) Noack, C.; Burggraf, F.; Hosseiny, S. S.; Lettenmeier, P.; Kolb, S.; Belz, S.; Kallo, J.; Friedrich, K. A. Studie Über Die Planung Einer Demonstrationsanlage Zur Wasserstoff-Kraftstoffgewinnung Durch Elektrolyse Mit Zwischenspeicherung in Salzkavernen Unter Druck. BMWi 2015, 298.

(16) Gielen, D.; Taibi, E.; Miranda, R. Hydrogen: A Renewable Energy Persepective; 2019.

(17) Saggiorato, N.; Wei, M.; Lipman, T.; Mayyas, A.; Chan, S. H.; Breunig, H.; Mckone, T.; Beattie, P.; Chong, P.; Colella, W. G.; James, B. D.; Lawrence, E. O.; Laboratory, B. N. A Total Cost of Ownership Model for Low Temperature PEM Fuel Cells in Combined Heat and Power and Backup Power Applications; 2017.

(18) James, B. D.; Desantis, D. A. Manufacturing Cost and Installed Price Analysis of Stationary Fuel Cell Systems; 2015.

(19) NREL. H2A: Hydrogen Analysis Production Models | Hydrogen and Fuel Cells | NREL https://www.nrel.gov/hydrogen/h2a-production-models.html (accessed Apr 15, 2020).

(20) Fan, J.; Wright, A. G.; Britton, B.; Weissbach, T.; Skalski, T. J. G.; Ward, J.; Peckham, T. J.; Holdcroft, S. Cationic Polyelectrolytes, Stable in 10 M KOHaq at 100 °c. ACS Macro Lett. 2017, 6 (10), 1089–1093. https://doi.org/10.1021/acsmacrolett.7b00679.

(21) Nguyen, T.; Abdin, Z.; Holm, T.; Mérida, W. Grid-Connected Hydrogen Production via Large-Scale Water Electrolysis. Energy Convers. Manag. 2019, 200, 112108. https://doi.org/10.1016/j.enconman.2019.112108.

(22) Lee, A. Goldwind Canada breakthrough for “world record low price” wind | Recharge https://www.rechargenews.com/wind/goldwind-canada-breakthrough-for-world-record-low-price-wind/2-1-656942 (accessed May 13, 2020).

DOCUMENT CHANGE HISTORY

Document ID	Document ID
FM-7024-B	Hydrogen Production cost by AEM electrolysis

Revision	Prepared By	Approved By	Effective Date
B	Omid Toussi	Ben Britton	Feb 3, 20201

This document is reviewed to ensure its continuing relevance to the systems and process that it describes.

REVISION HISTORY:

Revision	Date	Description of Changes	Approved By
A	June. 23,2020	Initial Draft	Bill Haberlin
B	Feb 3, 2021	Updated document design	Ben Britton